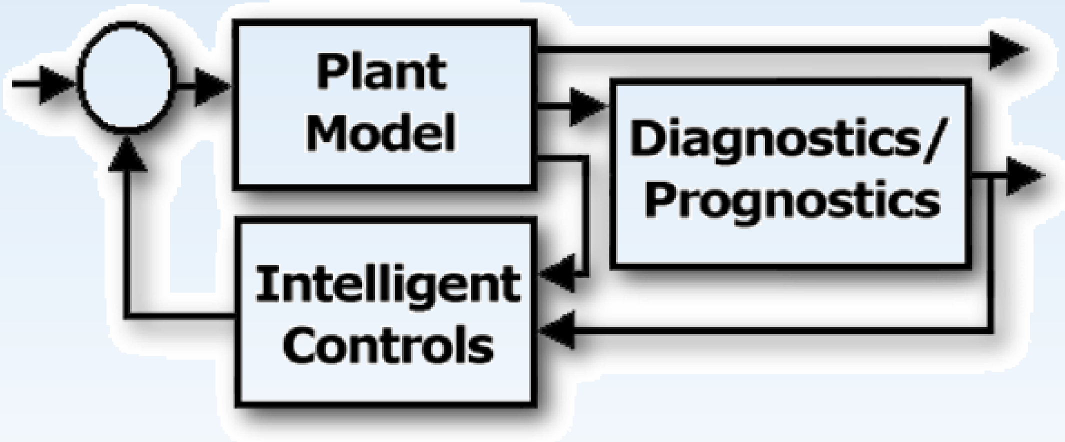
Challenges in Aircraft Engine Control and Gas Path Health Management



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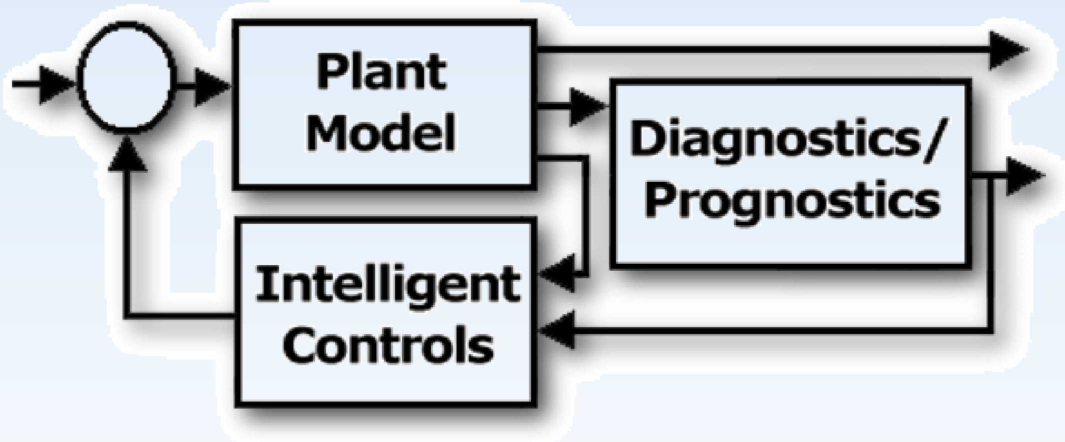
Challenges in Aircraft Engine Controls



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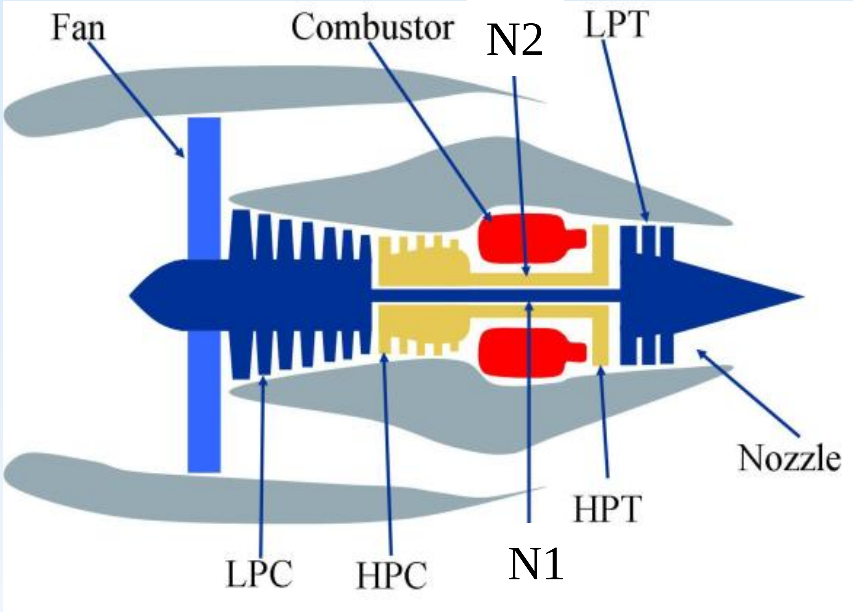
Outline

- Fundamentals of Aircraft Engine Control
- Intelligent Engine Concept – from a controls perspective
- Advanced Engine Control Logic
- Active Component Control
- Distributed Engine Control
- Summary

Turbofan Engine Basics



LPC - Low Pressure Compressor
HPC - High Pressure Compressor
HPT - High Pressure Turbine
LPT - Low Pressure Turbine
N1 - Fan Speed
N2 - Core Speed

- Dual Shaft – High Pressure and Low Pressure
- Two flow paths – bypass and core
- Most of the thrust generated through the bypass flow
- Core compressed air mixed with fuel and ignited in the Combustor
- Two turbines extract energy from the hot air to drive the compressors

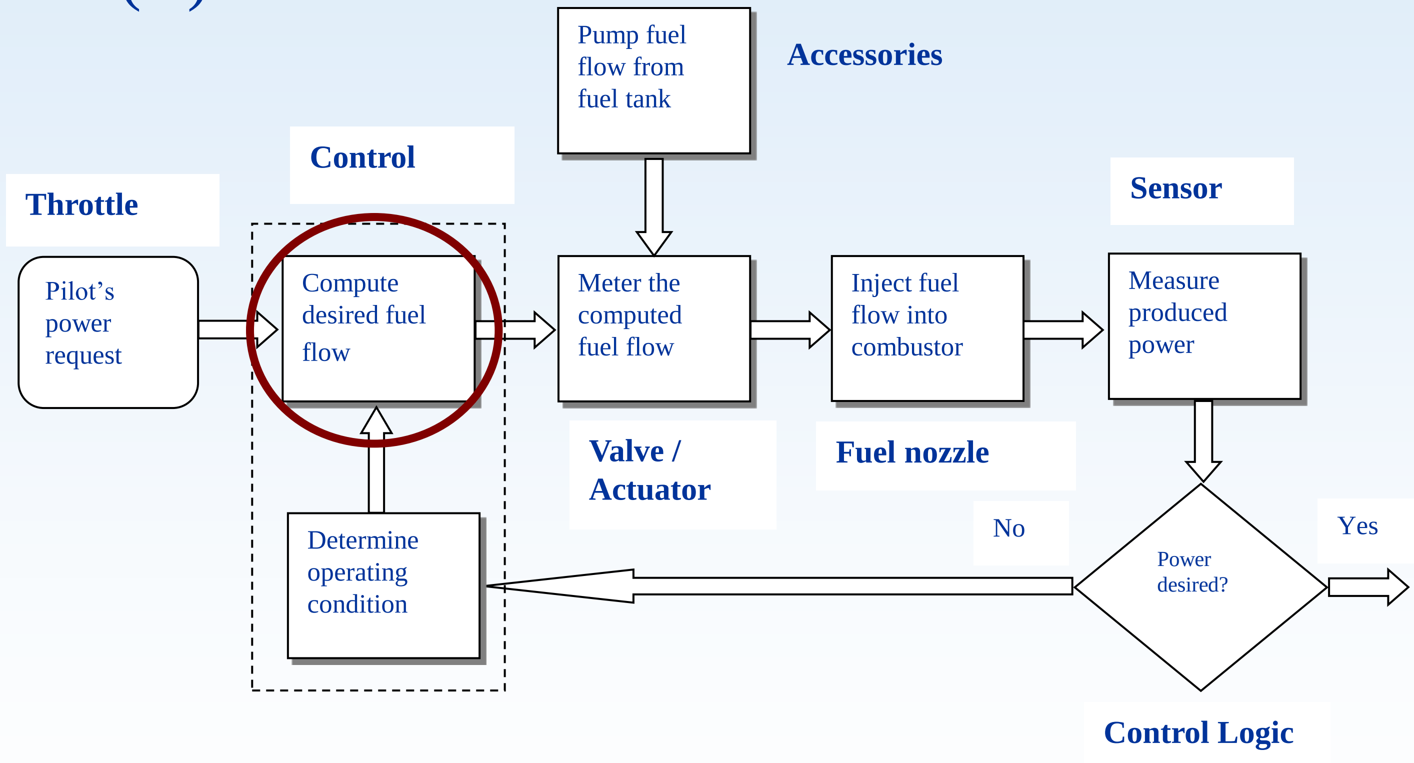
Basic Engine Control Concept

- **Objective:** Provide smooth, stable, and stall free operation of the engine via single input (PLA) with no throttle restrictions
    - Reliable and predictable throttle movement to thrust response

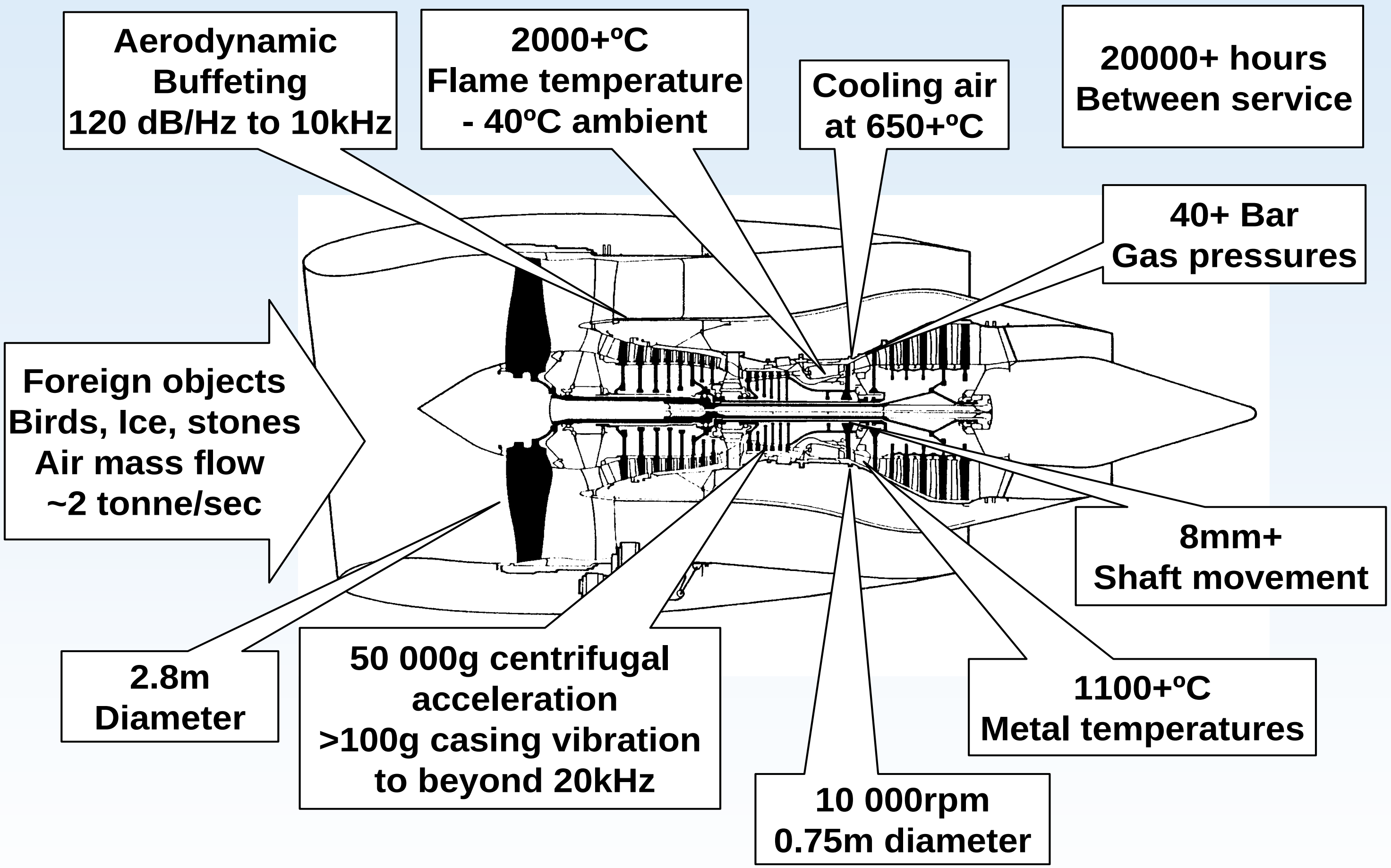
- **Issues:**
    - Thrust cannot be measured
    - Changes in ambient condition and aircraft maneuvers cause distortion into the fan/compressor
    - Harsh operating environment – high temperatures and large vibrations
    - Safe operation – avoid stall, combustor blow out etc.
    - Need to provide long operating life – 20,000 hours
    - Engine components degrade with usage – need to have reliable performance throughout the operating life

Basic Engine Control Concept

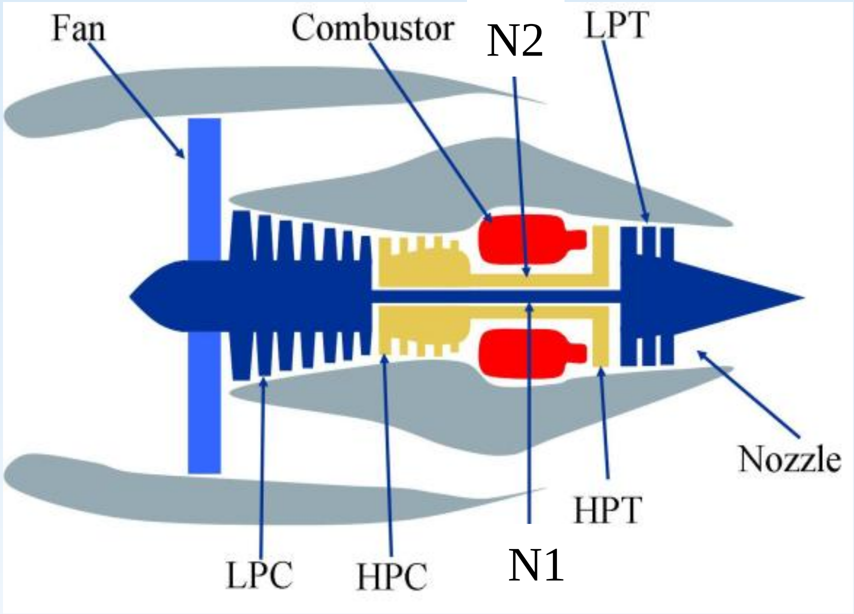
- Since Thrust (T) cannot be measured, use Fuel Flow WF to Control shaft speed N
  - T = F(N)



Environment within a gas turbine



Operational Limits



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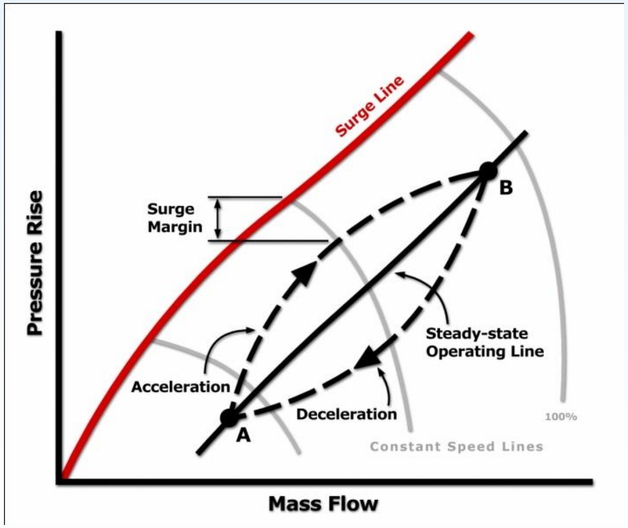
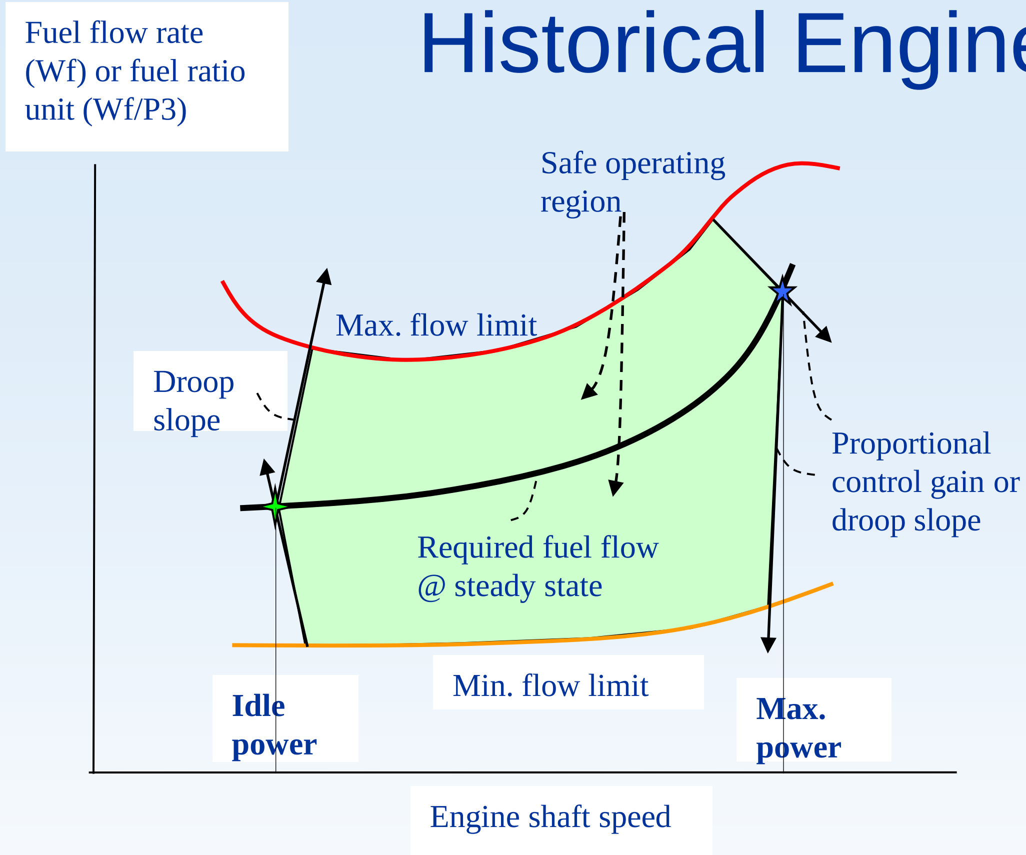
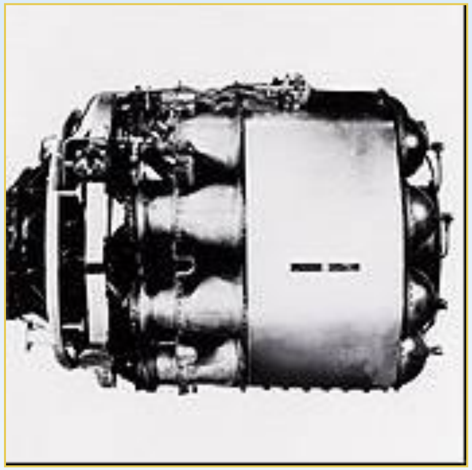


- **Structural Limits:**
  - Maximum Fan and Core Speeds – N1, N2
  - Maximum Turbine Blade Temperature
- **Safety Limits:**
  - Adequate Stall Margin – Compressor and Fan
  - Lean Burner Blowout – minimum fuel
- **Operational Limit:**
  - Maximum Turbine Inlet Temperature – long life

Historical Engine Control





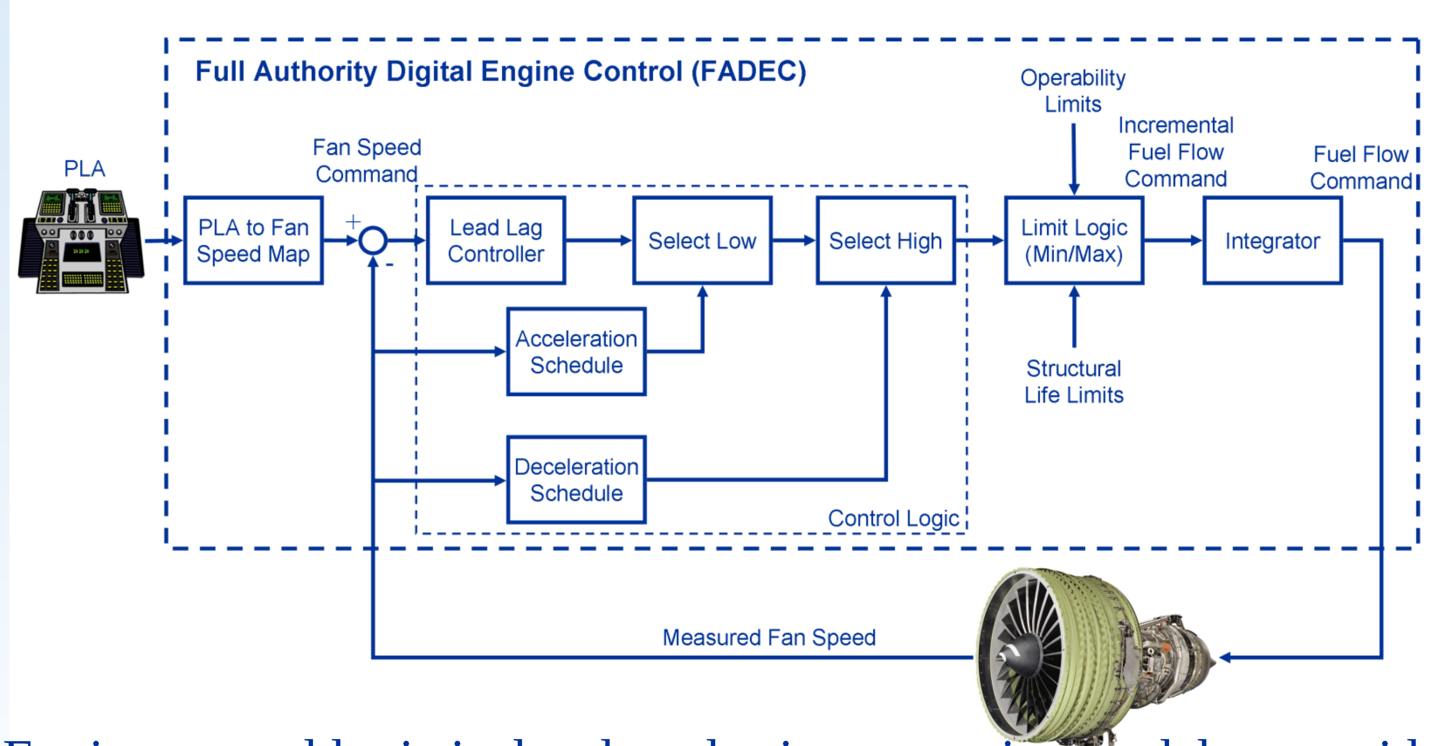
GE I-A (1942)

- Fuel flow is the only controlled variable.
  - Hydro-mechanical governor.
  - Minimum-flow stop to prevent flame-out.
  - Maximum-flow schedule to prevent over-temperature

- Stall protection implemented by pilot following cue cards for throttle movement limitations

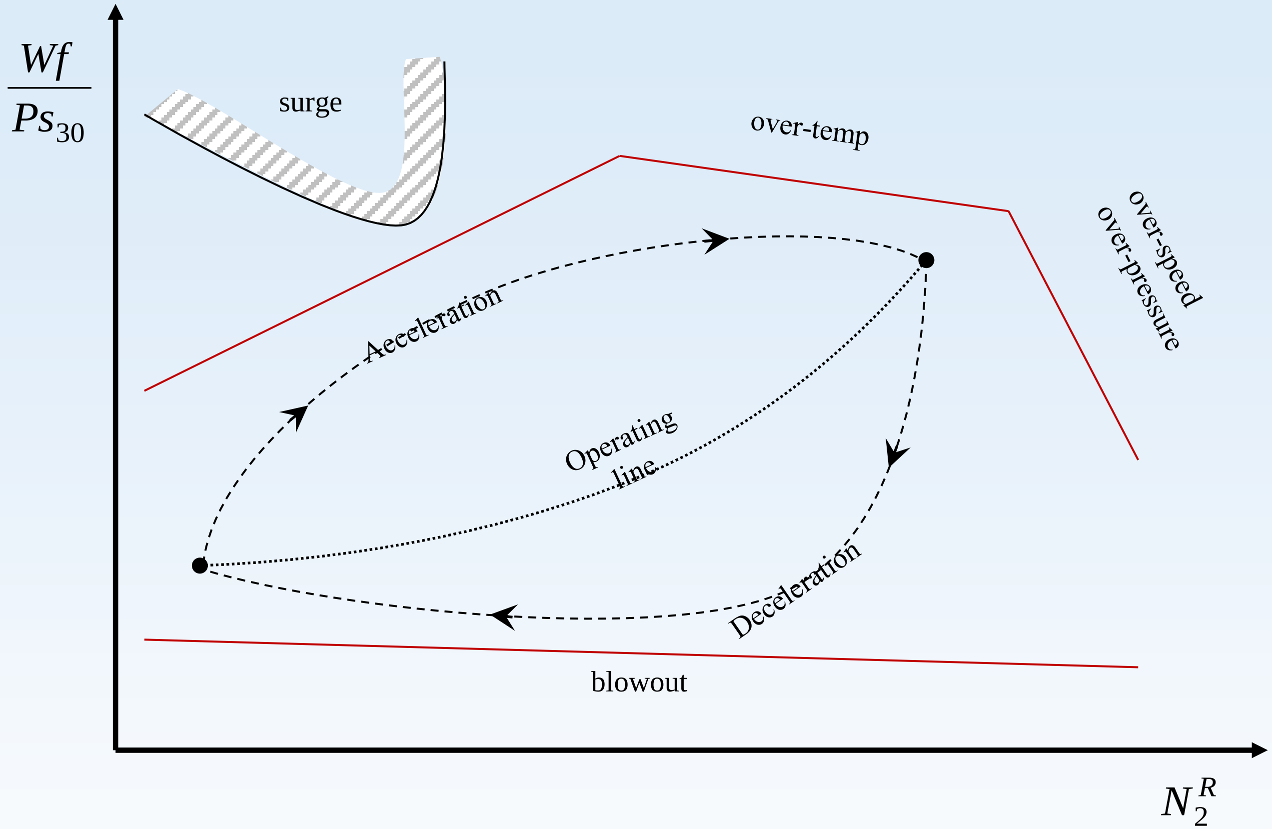
Typical Current Engine Control

- Allows pilot to have full throttle movement throughout the flight envelope
  - There are many controlled variables – we will focus on fuel flow



- Engine control logic is developed using an engine model to provide guaranteed performance (minimum thrust for a throttle setting) throughout the life of the engine
  - FAA regulations provide a maximum allowable rise time of 5 sec to reach 95% and a maximum settling time for thrust from idle to max

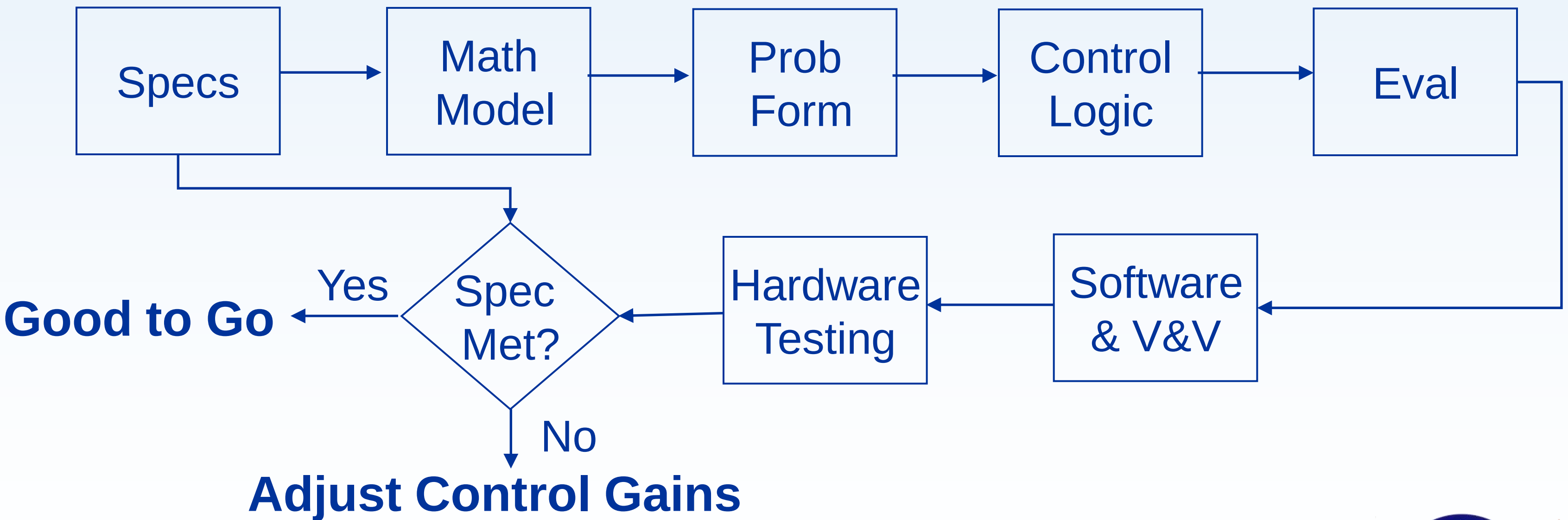
Implementing Limits for Engine Control



- Limits are implemented by limiting fuel flow based on rotor speed
  - Maximum fuel limit protects against surge/stall, over-temp, over-speed and over-pressure
  - Minimum fuel limit protects against combustor blowout
- Actual limit values are generated through simulation and analytical studies

Control Law Design Procedure

- The various control gains K are determined using linear engine models and linear control theory
  - Proportional + Integral control provides good fan speed tracking
  - Control gains are scheduled based on PLA and Mach number
- Control design evaluated throughout the envelope using a nonlinear engine simulation and implemented via software on FADEC processor
- Control gains are adjusted to provide desired performance based on engine ground and altitude tests and finally flight tests



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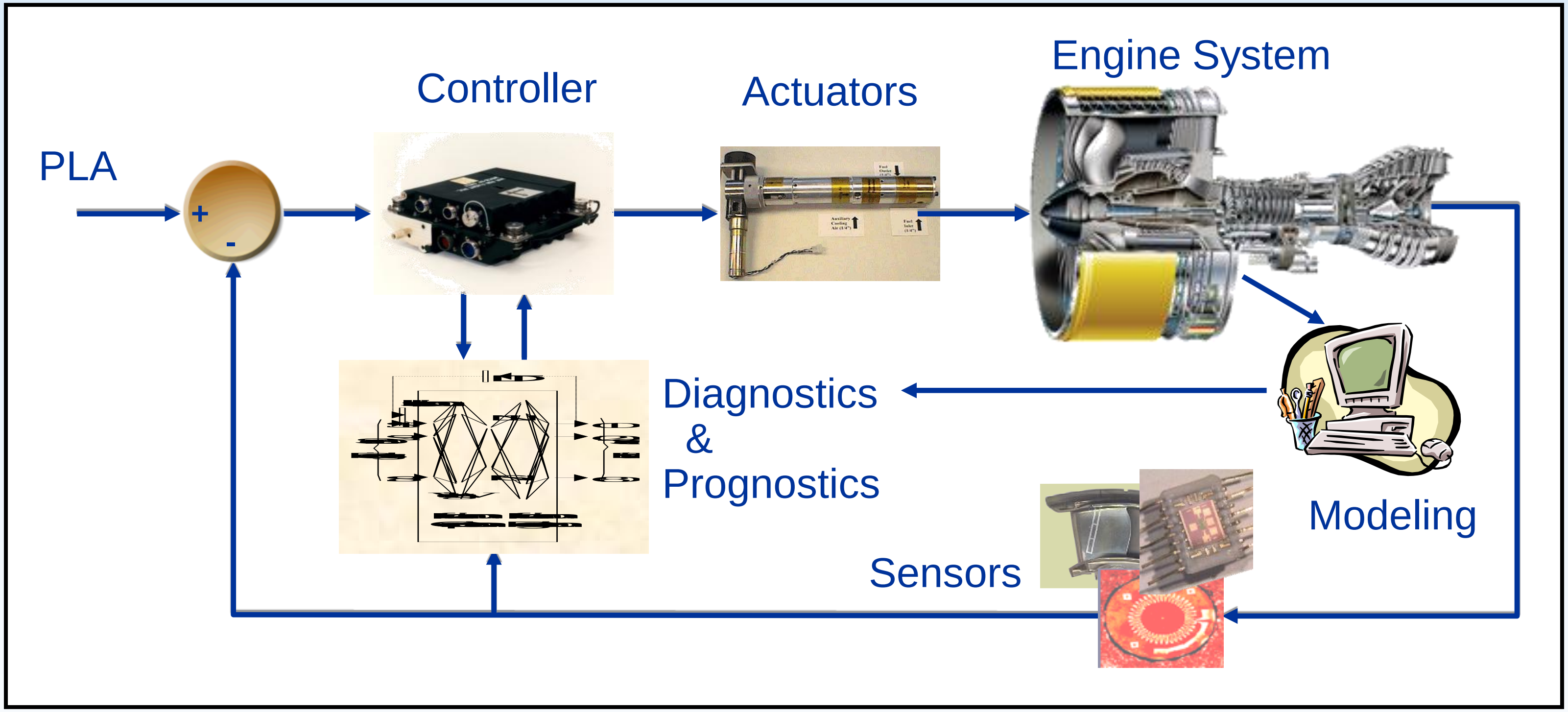
Intelligent Engine Technologies

- A Systems Viewpoint -

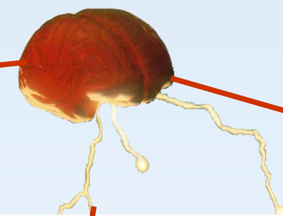


- Components such as actuators, sensors, control logic, & diagnostic systems have to be designed with overall system requirements in mind.

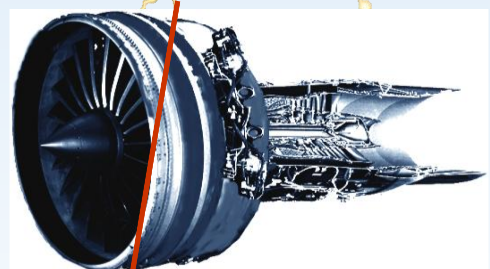
- Simplified models are essential for controller design. Understanding the physics of the phenomena is required to capture critical system dynamics in these models.

Intelligent Propulsion Systems
Control System perspective

Multifold increase in propulsion system Affordability, Capability Environmental Compatibility, Performance, Reliability and Safety



Active Control Technologies for enhanced performance and reliability, and reduced emissions
- active control of combustor, compressor, vibration etc.
- MEMS based control applications



Advanced Health Management technologies for self diagnostic and prognostic propulsion system
- Life usage monitoring and prediction
- Data fusion from multiple sensors and model based information

Distributed, Fault-Tolerant Engine Control for enhanced reliability, reduced weight and optimal performance with system deterioration
- Smart sensors and actuators
- Robust, adaptive control

Modeling Engine Faults and Performance Deterioration*

A general influence coefficient matrix may be derived for any particular gas turbine cycle, defining the set of differential equations which interrelate the various dependent and independent engine performance parameters.

Physical Problems

- Erosion
- Corrosion
- Fouling
- Built up dirt
- FOD
- Worn seals or excessive clearance
- Burned, bowed or missing blades
- Plugged nozzles

Result in →

← Permitting correction of

Degraded Component Performance

- Flow capacities
- Efficiencies
- Effective nozzle areas
- Expansion coefficients

Producing →

← Allowing isolation of

Changes in Measurable Parameters

- Spool speeds
- Fuel flow
- Temperatures
- Pressures
- Power output

* From "Parameter Selection for Multiple Fault Diagnostics of Gas Turbine Engines" by Louis A. Urban, 1974

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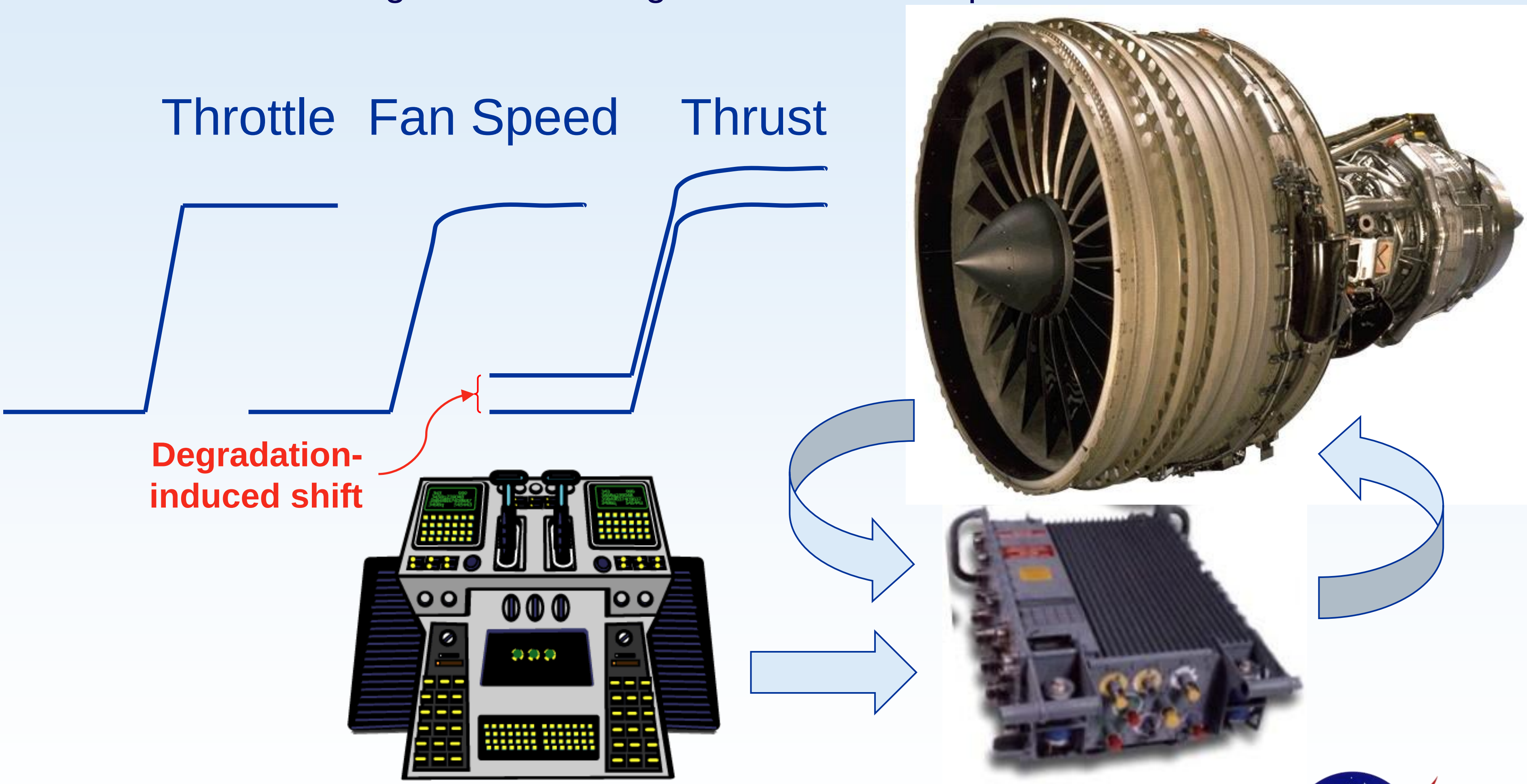
Advanced Engine Control Logic

- Multi-variable Control (MVC) – extensive research on engine application in the mid1970s-90s
  - LQR based MVC demonstrated on F-100 engine at NASA GRC in 1979
  - LQG/LTR based engine control studies in mid 1980s with engine test in UK
  - H-infinity based robust engine control studies at NASA GRC in mid 1990s
- Life Extending Control demonstrated in simulation studies at GRC in early 2000s
  - Modify the acceleration logic to increase on-wing life while still meeting the performance requirements
- Various research studies on Sensor Fault Detection, Isolation and Accommodation

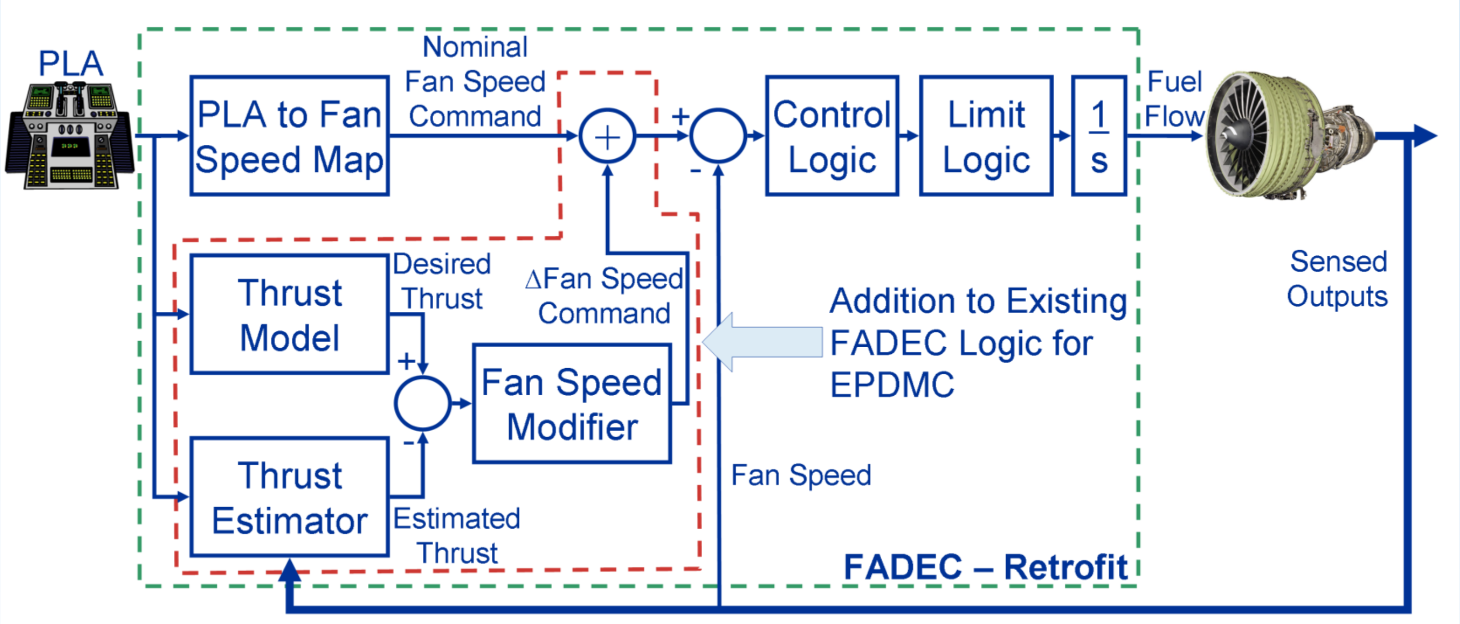
Engine Performance Deterioration Mitigation Control

• Motivation—Thrust-to-Throttle Relationship Changes with Degradation in Engines Under Fan Speed Control



EPDMC Architecture

- The proposed retrofit architecture:

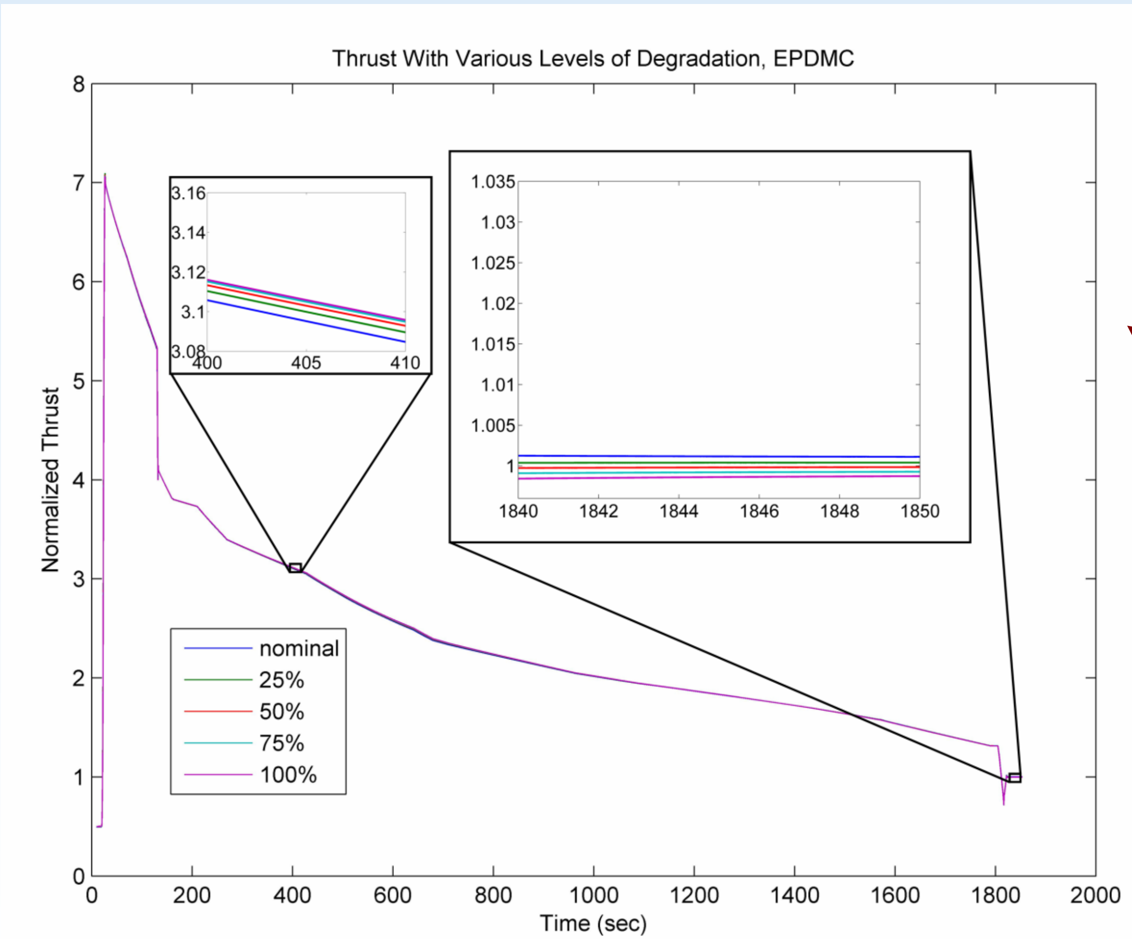


- Adds the following “logic” elements to existing FADEC:
  - A model of the nominal throttle to desired thrust response
  - An estimator for engine thrust based on available measurements
  - A modifier to the Fan Speed Command based on the error between desired and estimated thrust
    - Since the modifier appears prior to the limit logic, the operational safety and life remains unchanged

EPDMC Evaluation

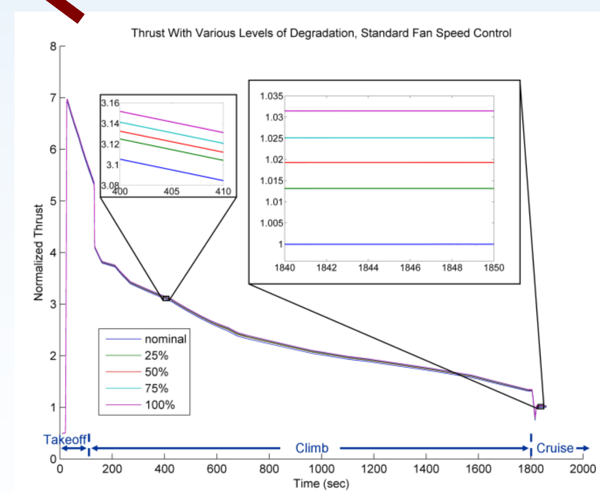
Thrust response for Typical Mission

With EPDMC

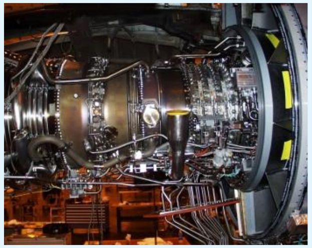


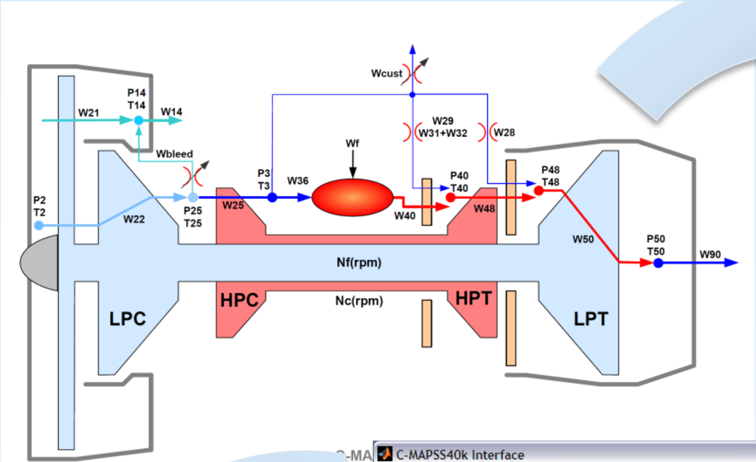
- **Throttle to thrust response is maintained – no "uncommanded" thrust asymmetry**

Without EPDMC

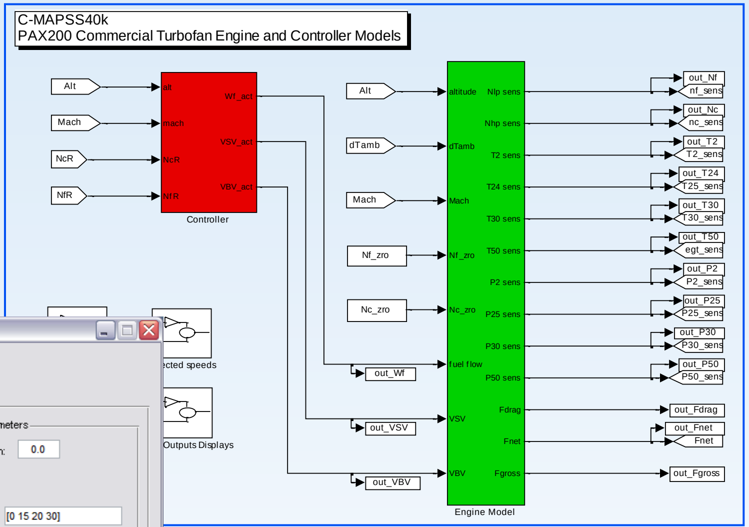


Commercial Modular Aero-Propulsion System Simulation 40k



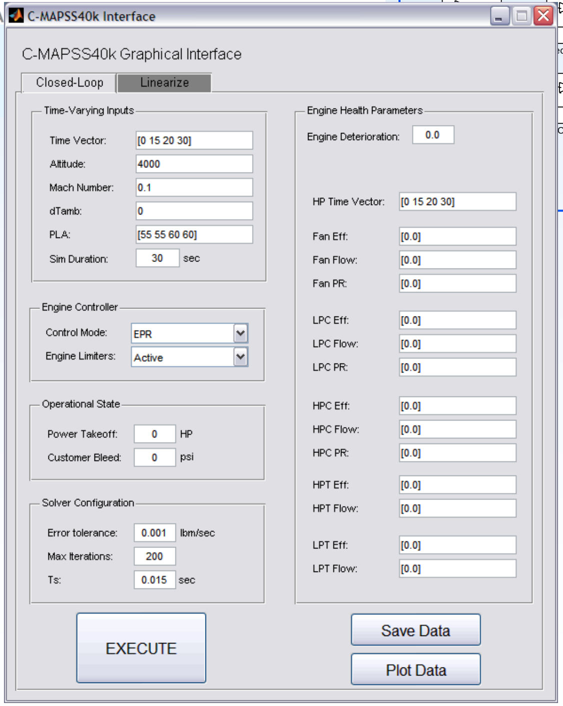


Simulation programmed in graphical language

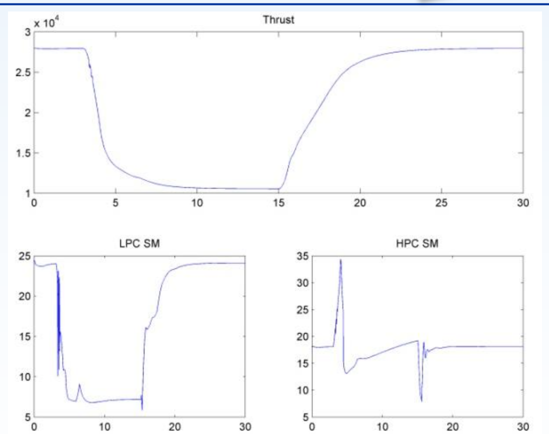


Engine flight data used to tune physics-based model

Plotting and graphical analysis capability



GUI driven operation

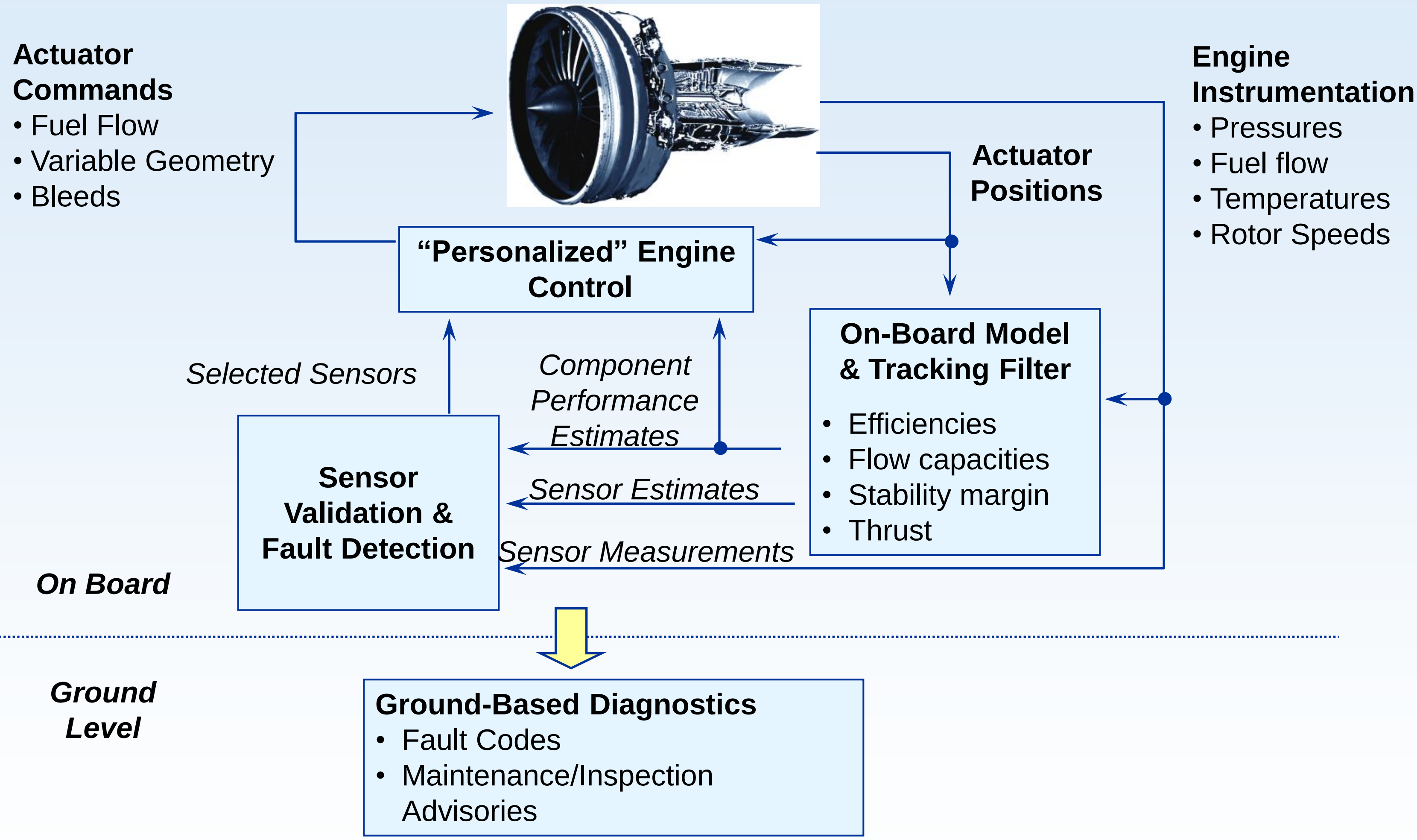


C-MAPSS40k thrust and stall margin response to throttle movements

Glenn Research Center

at Lewis Field

Model-Based Control and Diagnostics Concept

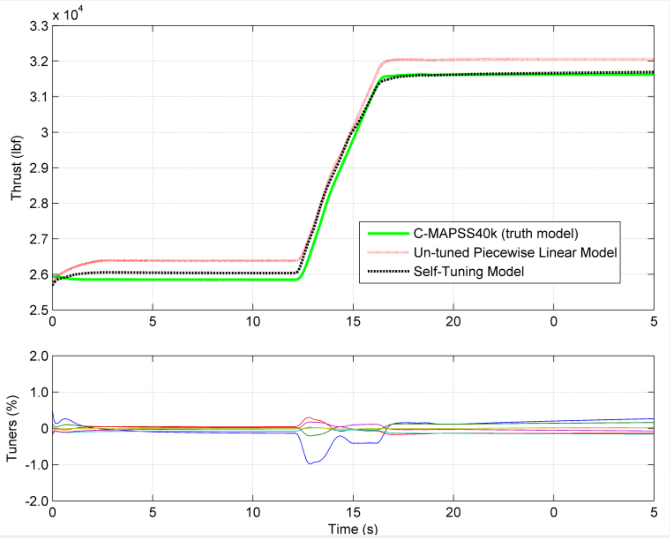


Model-Based Engine Control

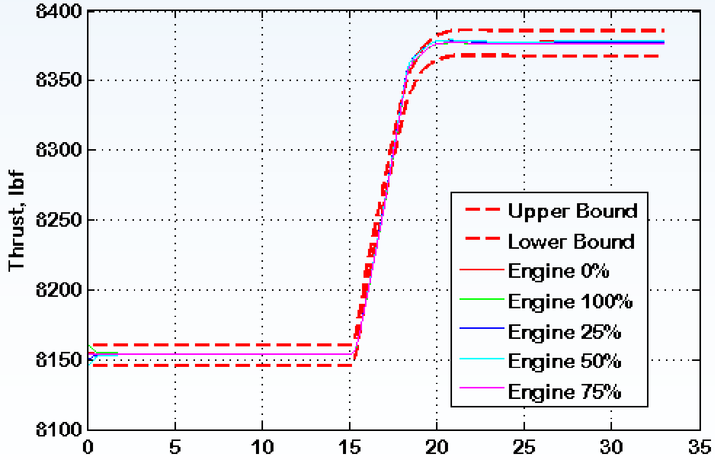
Objective: Develop and demonstrate the capability to provide more efficient engine control using an on-board real-time model.

Approach:

- Develop a self-tuning engine model for the C-MAPSS40k engine simulation – using the optimal tuner approach
- Validate the self-tuning model's ability to track changes in engine gas path performance parameters
- Develop direct thrust and limited variable control using model based estimated value



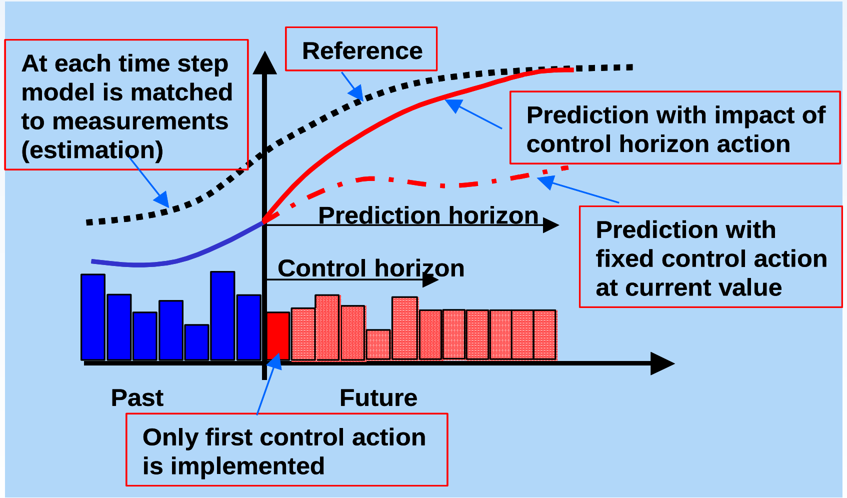
Self-tuning engine model vs. "un-tuned" piecewise linear model response (top), and corresponding model tuning parameter adjustments (bottom)



Tight control of Thrust achieved – preliminary linear design

Adaptive Engine Control

- The traditional engine control logic consists of a fixed set of control gains developed using an average model of the engine
- Having an on-board engine model which “adapts” to the condition of the engine, opens up the possibility of adapting the control logic to maintain desired performance in the presence of engine degradation or to accommodate any faults while obtaining best achievable performance
- An emerging technique for such an adaptive engine control is the Model Predictive Control (MPC)



- MPC solves a constrained optimization problem online to obtain the “best” control action - based on a tracked engine model, constraints, and the desired optimization objective

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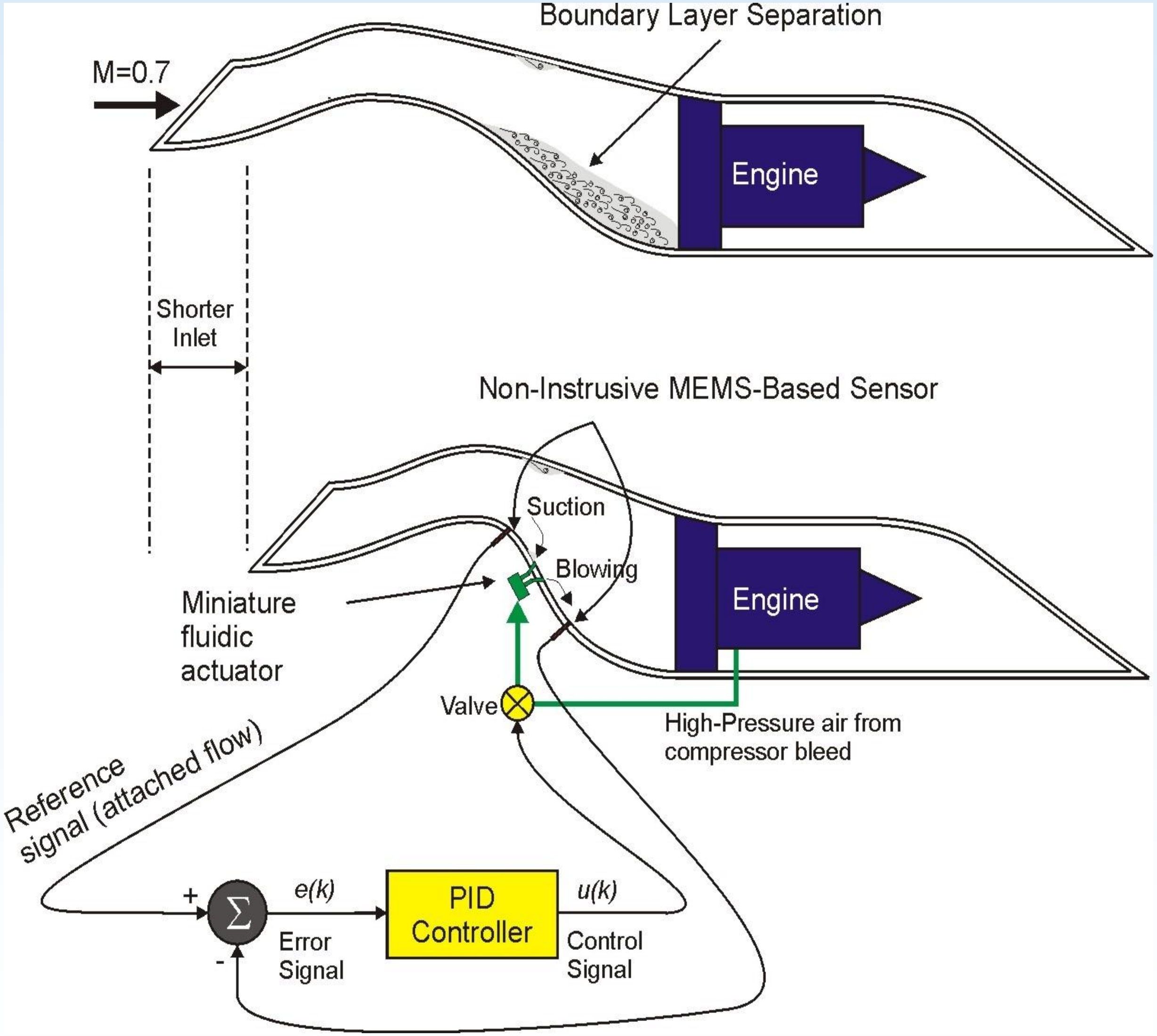
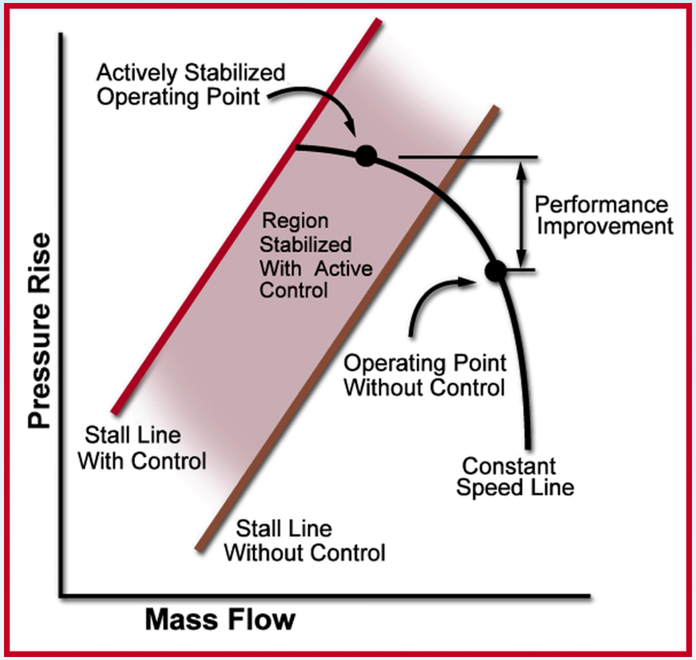
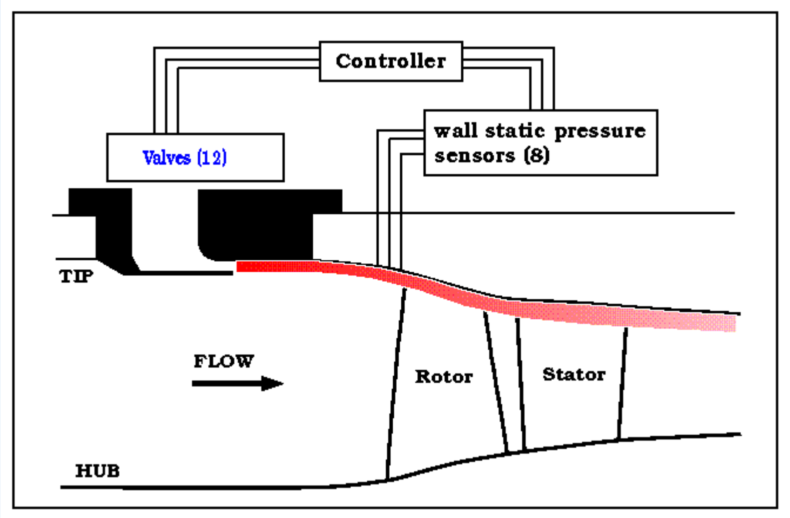
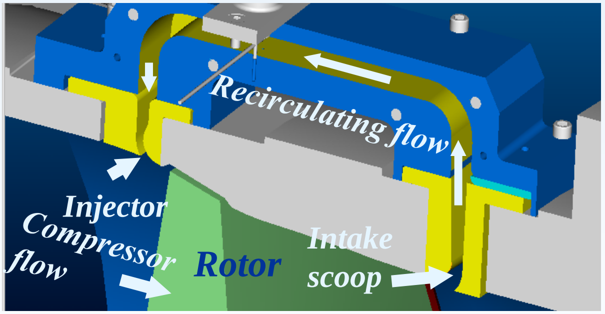
Separation Control in Intake Ducts



Active Stall Control







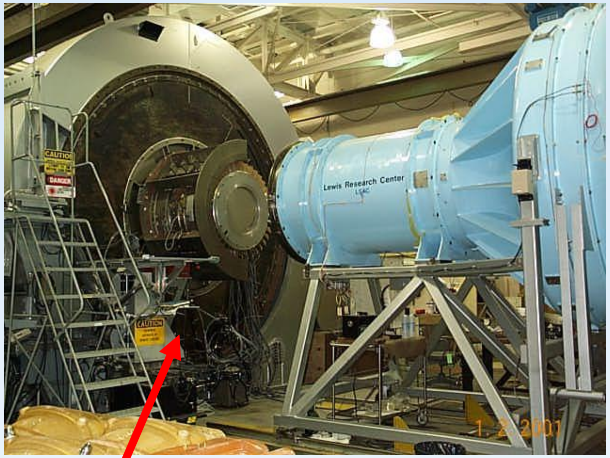
Compressor Stability Enhancement Using Recirculated Flow

- Detect stall precursive signals from pressure measurements.
- Develop high frequency actuators and injector designs.
- Actively stabilize rotating stall using high velocity air injection with robust control.

- Demonstrated significant performance improvement with an advanced high speed compressor in a compressor rig with simulated recirculating flow

Active Flow Control - Compressors

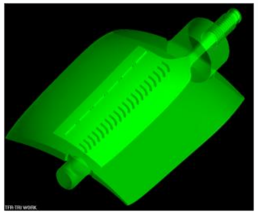
Compressor Stator Suction Surface Separation Control

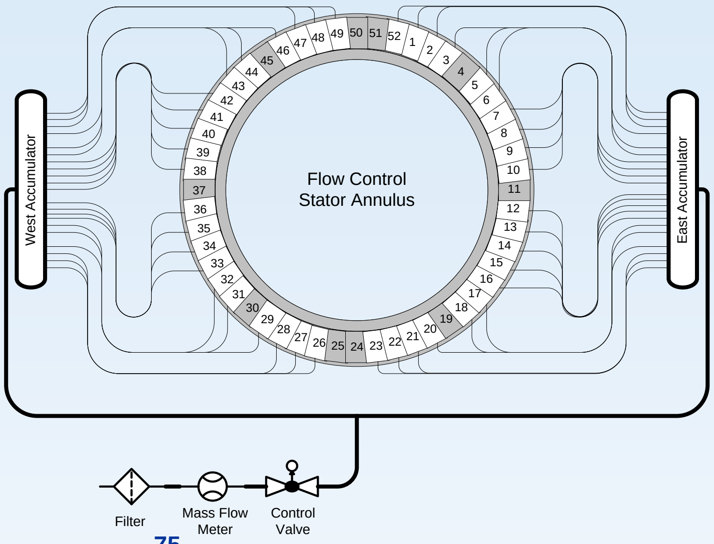


Multistage Axial Compressor

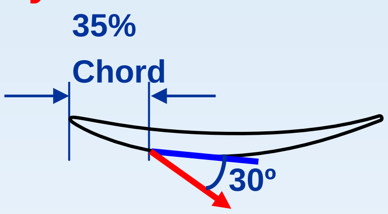
Installed Smart Vane Stators

Rapid Prototype
Flow Control Vane

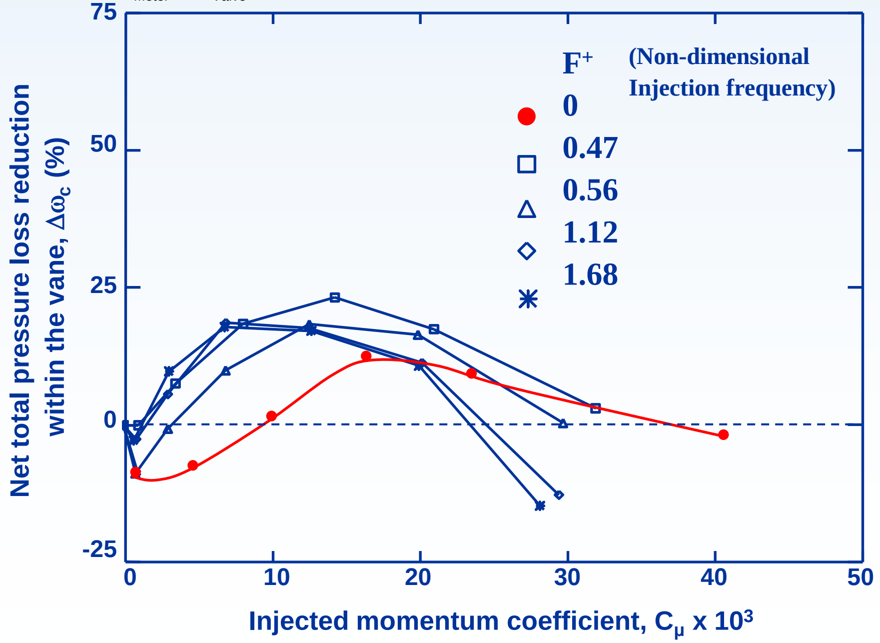




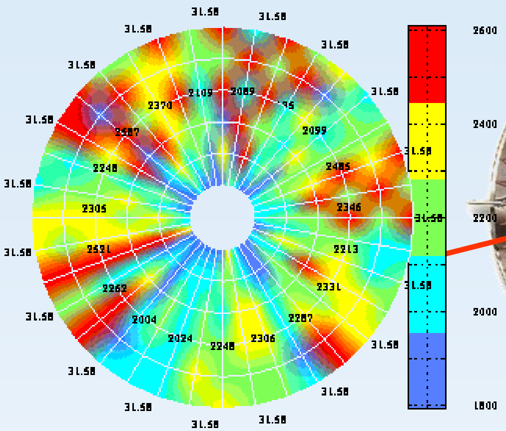
Flow Delivery
System

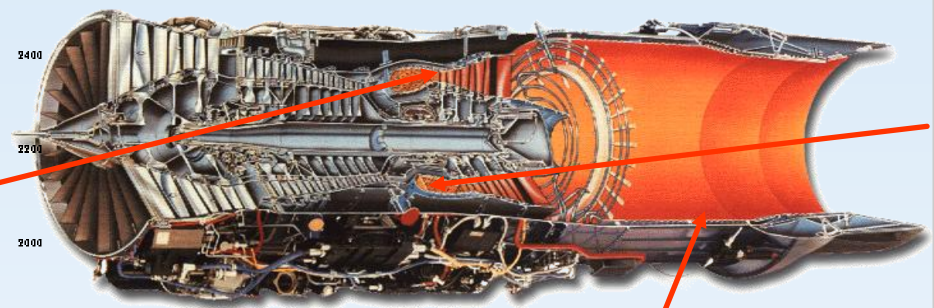


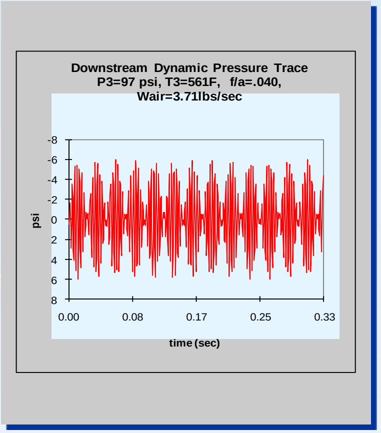
Flow
Injection



Active Combustion Controls



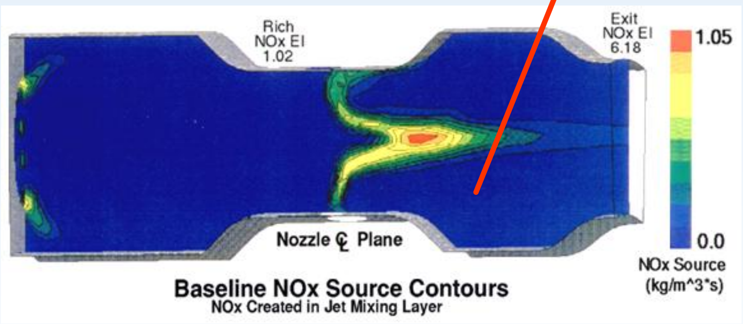




Pattern Factor Control

Objective: Actively reduce combustor pattern factor

Status: Concept demonstrated in collaboration with Honeywell Engines under the AST program - 2000.



Emission Minimizing Control

Objective: Actively reduce NOx production

Status: Fuel actuation concept and hardware developed under AST program. Preliminary low order emission models developed under the HSR program 2000.

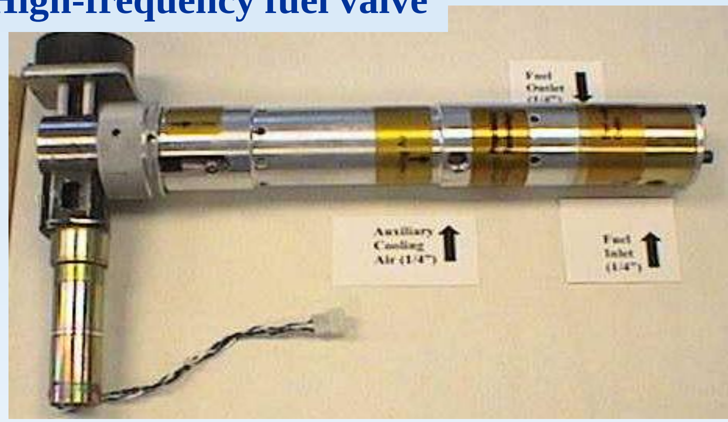
Combustion Instability Control

Objective: actively suppress thermo-acoustic driven pressure oscillations

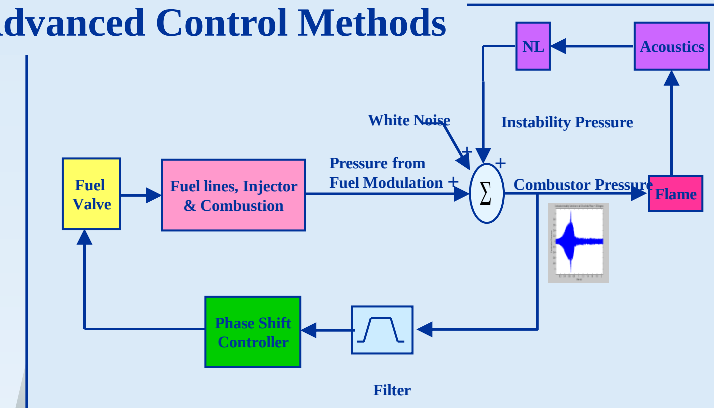
Status: Concept demonstrated on a single combustion rig in 2003. Continuing research under current projects.

Active Control of Combustion Instability

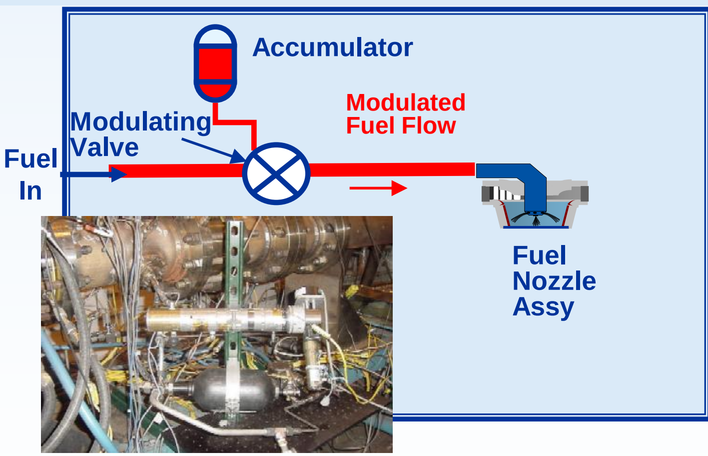
High-frequency fuel valve

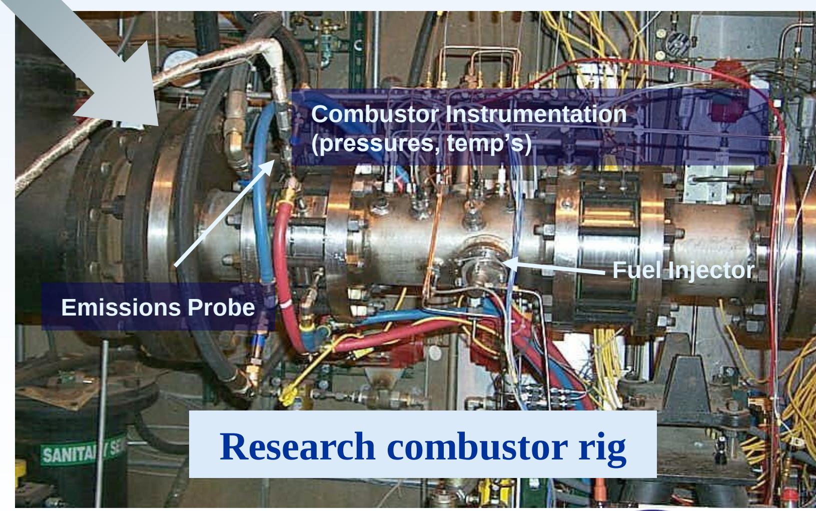


Advanced Control Methods



Fuel delivery system model and hardware

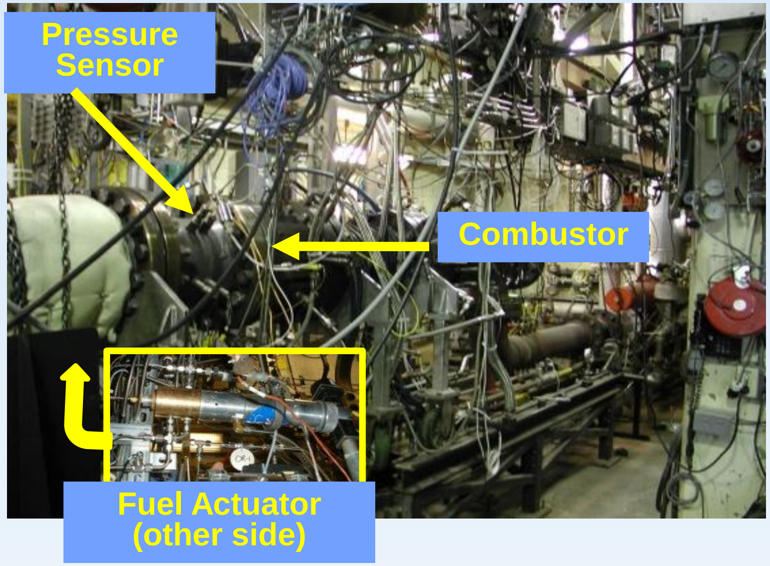


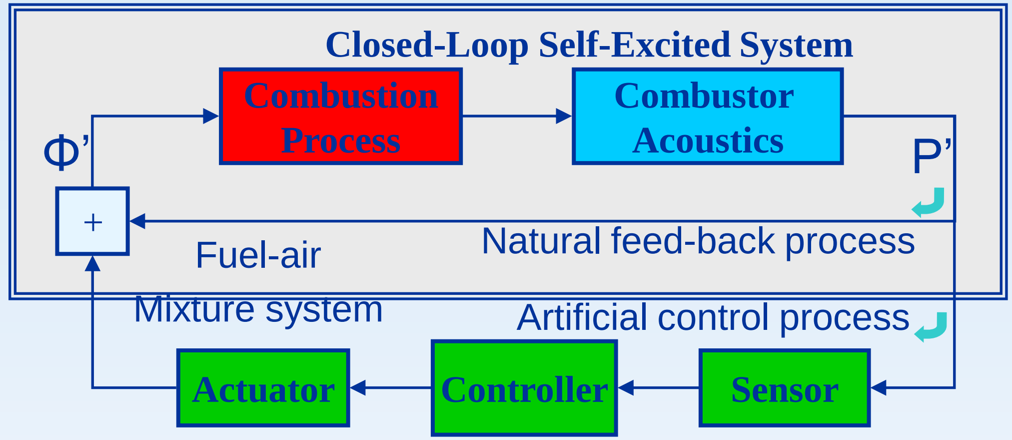


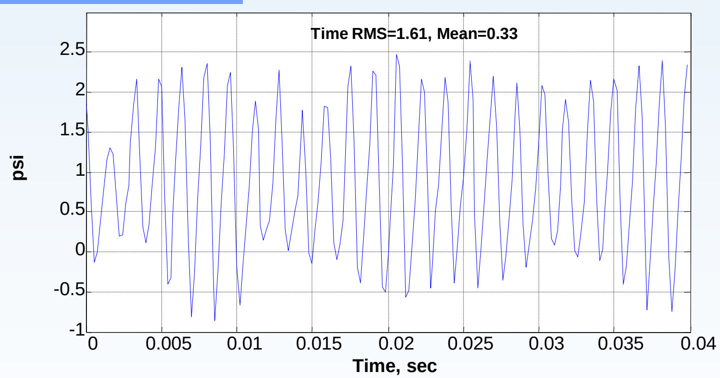
Research combustor rig

Active Instability Control on a Low Emission Combustor Prototype

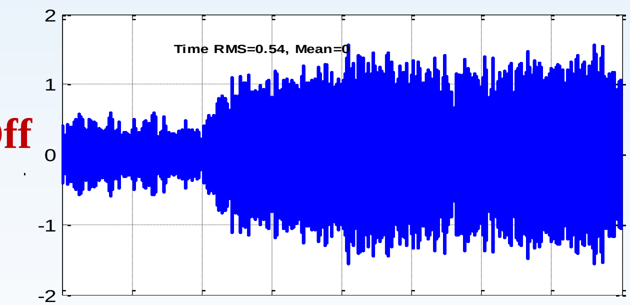
Results from testing Oct-Nov 2011



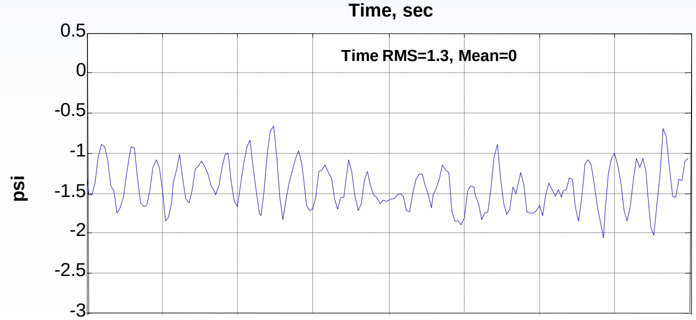




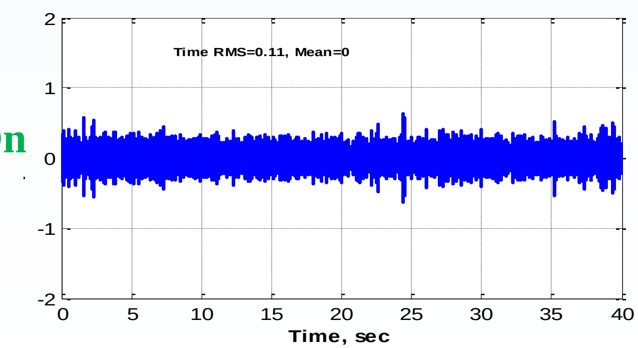
Controller Off



Instability Prevention



Controller On

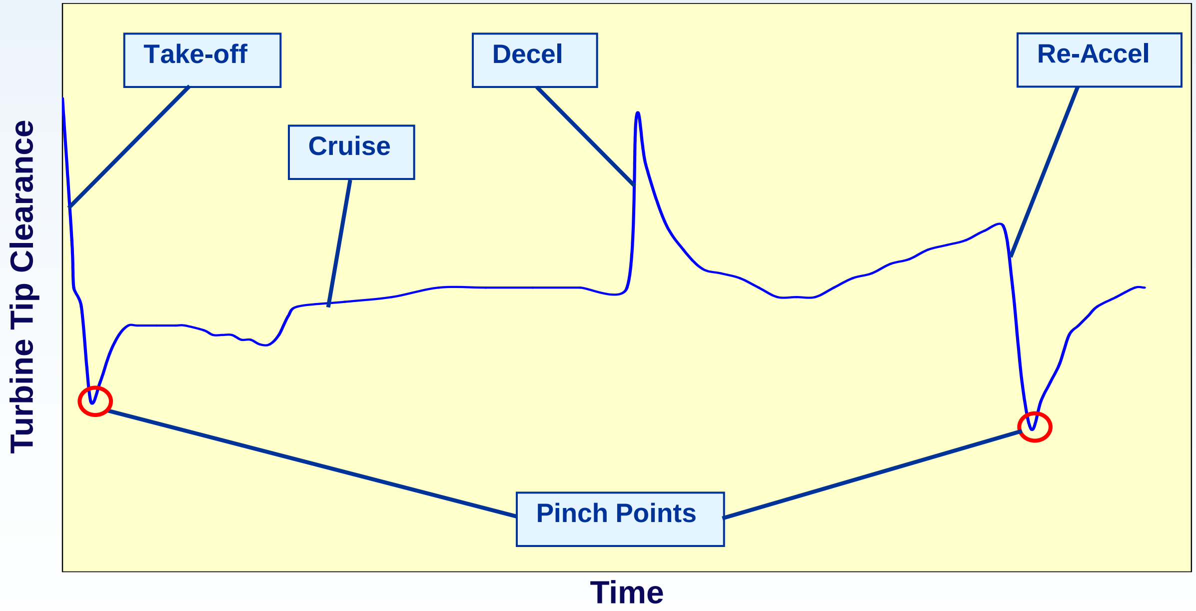


Instability Suppression

Intelligent Management of Turbine Tip Clearance

Time Scales:	Flights	Minutes	Seconds	Milliseconds
Problem:	Engine Wear	Cruise Clearance	Pinch Points	Eccentric Shaft Motion
Approach:	Regen. Seals	Case Cooling	Case Actuation	Magnetic Bearings

Notional Mission Profile



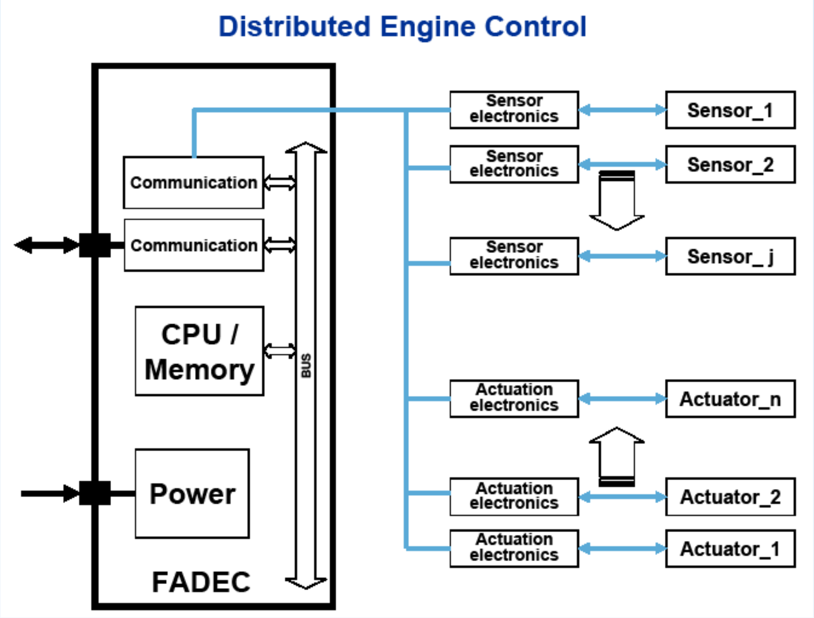
Outline

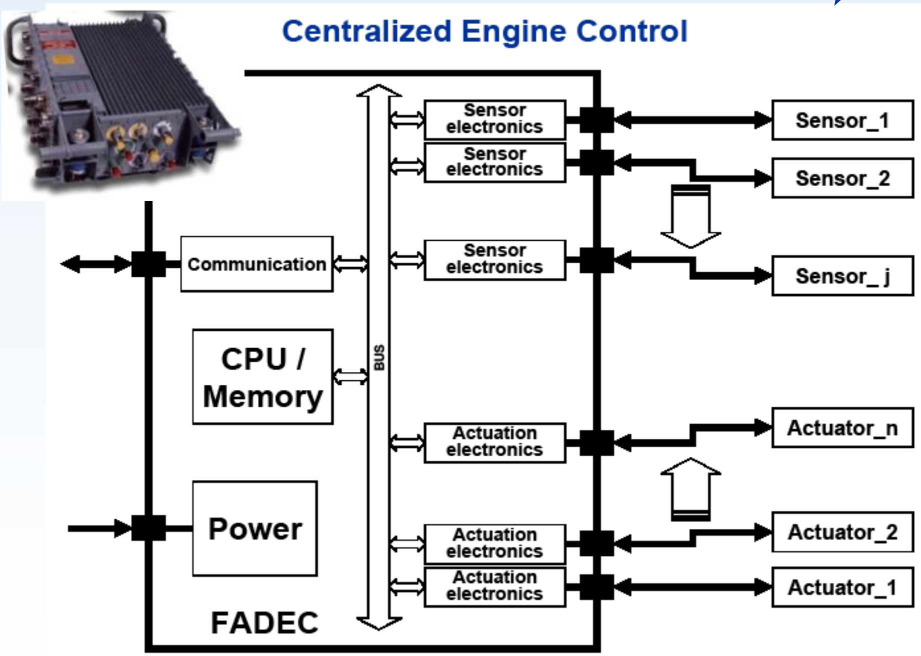
- Fundamentals of Aircraft Engine Control
- Intelligent Engine Concept – from a controls perspective
- Advanced Engine Control Logic
- Active Component Control
- **Distributed Engine Control**
- Summary

Distributed Engine Control

Objectives:

- Enable new engine concepts
- Enable new engine performance enhancing technologies
- Improve reliability
- Reduce overall cost
- Reduce control system weight





Challenges:

- High temperature electronics
- Communications based on open system standards
- Control function distribution

Government – Industry Partnership

Distributed Engine Control Working Group

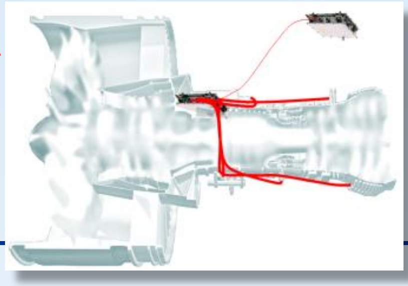
Distributed Control Technology Roadmap

T=0 years 5 10 15 20

CORE I/O

Core-Mounted :
Data Concentrator
Digital Communications
Distributed Power

SOI µP, logic, analog
SiC power

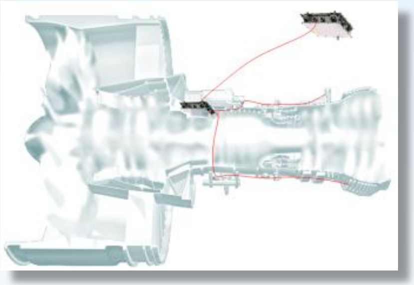


Hardware-in-the-Loop Facility

NETWORKED CONTROL

Engine Network
Smart System Devices
>300 Celsius Electronics

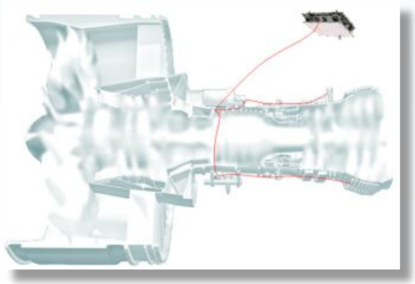
SOI µP, logic, analog
Medium Scale Integration SiC µP, logic, analog
SiC power



FULLY DISTIBUTED

Common Network Communications (Wireless)
Embedded Control Law
Embedded Power Harvesting

SOI µP, logic, analog
Large Scale Integration SiC µP, logic, analog
SiC power



Summary

- There are tremendous opportunities to improve and revolutionize aircraft engine performance through “proper” use of advanced control technologies
  - Intelligent engine control integrated with reliable condition monitoring and fault diagnostics to extend on-wing operating life, maintain performance with aging, safely accommodate faults while maintaining best achievable performance etc.
  - Active control of engine components to provide the desired performance characteristics throughout the flight envelope and enable low emission higher performance components
  - Distributed engine control to enable new engine concepts, reduce “control system” weight, increase operational reliability, and flexibility to easily incorporate new and improved capabilities

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NASA TMs are available for free download at:
http://ntrs.nasa.gov/search.jsp

Engine Simulation Software C-MAPSS40k – available to U.S. citizens
http://sr.grc.nasa.gov/public/project/77/